AN APPARATUS AND METHOD FOR GENERATING AN OPTICAL SINGLE
SIDEBAND SIGNAL

5   Description.

The present invention is concerned with optical single
sideband (OSSB) transmission and, more particularly, to wave
division multiplexing (WDM) SSB signals.

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Single sideband (SSB) offers some convincing advantages over
conventional double sided transmission. In conventional
optical modulation formats, two information sidebands are
transmitted, commonly referred to as optical double sideband

15   (ODSB) transmission. By contrast, optical single sideband
(OSSB) signals suppress one of the sidebands in order to
reduce the frequency occupation of the transmitted signal.

The situation will be better understood by comparing the

20   single sideband of Fig. 1a to that of the double sideband
transmission of Fig. 1b. As can be seen, the SSB signals 102
in Fig. 1a require half of the bandwidth of that of the
double sided signals 104 in Fig. 1b. In other words, the
spectral occupancy of the SSB signals is effectively halved

25   in the SSB case, thereby doubling the number of transmitted
channels available as compared with conventional systems.

Another reason to utilize SSB, which is not readily seen from
these figures, is that OSSB signals have higher tolerance to

30   chromatic dispersion introduced by the optical transmission
fiber. In addition, OSSB signal technology provides
efficient electrical equalization at the receiver side due to
phase conservation after optical signal detection. Given
these grounds, it is easy to explain why SSB is a chief

35   method of transmission.

Not surprisingly, this has led to the development of the
field of generating an OSSB signal. Two different approaches
concern us here. The first is the use of an optical
configuration and electrical signals that produce the desired
5   optical signal. The second is the use of an optical filter
with a detuned central frequency. In the first situation, a
complete optical transmitter would be required, composed of
an optical source and an external modulator device. However,
providing an entire optical transmitter and modulator is
10   quite costly, if not impractical. In the second, the optical
signal may be generated by a third party or remote equipment
owing to the fact that the undesired optical sideband is
suppressed in the optical domain. However, as we shall see,
suppressing the sideband without distortion in the optical
15   domain is not so easily achieved.

Further, one must keep in mind whilst preparing the SSB
signal that the signal will likely be transmitted via
wavelength division multiplexing (WDM). WDM increases the
20   carrying capacity of the physical medium (fiber) by assigning
incoming optical signals to specific frequencies of light
(wavelengths, or lambdas) within a certain frequency band.
In a WDM system, each of the wavelengths is launched into the
fiber, and the signals are demultiplexed at the receiving
25   end. Further, each WDM channel has its own dedicated
bandwidth, meaning that all signals arrive at the same time,
rather than being broken up and carried in time slots.

Given the savings of bandwidth that is already achievable
30   with SSB signals, it would be clearly an advantage to
transmit SSB signals via WDM. However, in order to do this
the optical signals must have SSB properties before
multiplexing (or, at least, have SSB properties due to the
multiplexing process). Three known techniques have been
35   proposed for this purpose. It has been proposed, for
example, to optically generate the signal with SSB properties
at the transmitter equipment. Another proposal has been to

provide that the WDM equipment converts the incoming optical
signal to the electrical domain and use a complete optical
transmitter to generate the optical signal with the SSB
properties. Finally, it has been put forth to detune the
5   optical multiplexer in relation to the central wavelength of
each optical channel.

The first technique above requires the use of dedicated
transmitter equipment for WDM systems that are specially
10   designed for such purpose. The second technique is less cost
effective as we are doubling the required number of optical
transmitters. The third technique is highly cost effective,
although the properties of the SSB signal, namely the amount
of suppression of the undesired sideband and eye pattern
15   distortion introduced, depend strongly on the characteristics
of the used optical filter.

The problems with the third technique will be brought to
light with reference to Figs. 2a and 2b. In both of these
20   figures, an optical input signal 202 is filtered using a
detuned filtering characteristic 204. It is known that, when
the filter is detuned, the filtering characteristic has a
better opportunity to track the input optical signal.
However, as can be seen, a distortion in the characteristics
25   causes the filtered signal, the resulting SSB signal 206 to
be improperly filtered. The result is an SSB signal that is
inadequate in practice.

Henmi, U.S. Patent 5,227,908, discloses such a device,
30   reproduced here in Figure 3, to suppress one of the sidebands
using an optical filter. More particularly, Henmi's
transmitting side 300 is responsible for the SSB suppression
and it is this section that forms the focus of the instant
discussion. Briefly, a semiconductor laser 301 oscillates at
35   a carrier light frequency by a d.c. injection current from a
d.c. biasing source 302. An output light 304 is modulated by
an external modulator 305 driven by a transmitting signal

inputted from a terminal 303 and, after being passed through
an optical filter 307 which serves to suppress the side-band
signal component, the light 306 becomes a transmitting signal
light 308.

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However, the Henmi device has also proven deficient in
providing an SSB signal that accurately represents the
information in the input optical signal. It is postulated
that the reason lies in the fact that the Henmi device, i.e.,

10   section 300, generates the SSB signal within the optical
domain. Optical filtering, as proposed by Henmi, is unable
to obtain a good suppression of one sideband without
attenuating the optical carrier. The performance of the
technique proposed by NEC depends highly on the filter

15   characteristics, namely of the decay rate.

This is clearly illustrated by Figures 4a-4c. In Figure 4a,
a large number of channels 402 share an optical fiber to the
extent that the individual signals overlap resulting in

20   crosstalk. This may occur, for example, in a WDM system that
is dense, e.g., 40 Gb/s channels with 50 GHz frequency
spacing, when a broadband optical multiplexer is used to
aggregate the optical signals. When cross talk occurs 404, it
is not possible to filter the combined channel. This can be

25   seen from Figure 4b where the filters 406 intersect
neighboring channels. This results in the multiplexed signal
408 shown in Figure 4c, which has limited overall
performance.

30   Systems such as those proposed by Henmi suffer from such
consequences. One problem with such a solution is the
precision required for the optical multiplexer and possible
differences between the detuned frequency of the multiplexer
and the channel optical carrier frequencies (due to

35   temperature stability, etc).

It would be advantageous, therefore, to provide an OSSB
signal that accurately represents the input optical signal.
It is lacking in the art to provide a filter that accurately
5   suppresses one side band of the input optical signal.
Heretofore, there is not provided a means to accurately
single sideband filter an input optical signal taking into
account the cross talk appearing due to the combination of
several signals in a multiplexed signal.
10

Summary Of The Invention.

A single sideband signal (504) is generated from an input
optical signal (502). An optical phase modulator (508)
15   performs optical phase modulation on the input optical signal
(502) in accordance with a control signal (520) to produce
the single sideband signal (504). A converter (512) converts
the input optical signal (502) into a corresponding
electrical signal. A control signal generator (514, 516)
20   generates the control signal (520) in response to an optical
signal pulse shape of the input optical signal (502).

A single sideband signal is generated from an input optical
signal by converting a portion of the input optical signal
25   and converting such portion to an electrical signal. The
electrical signal is used to generate a control signal on the
basis of an optical signal pulse shape of the input optical
signal. Finally, an optical phase modulation of the input
optical signal is applied, based on the control signal.
30

An aim in the invention is to provide an adequately filtered
OSSB signal for wave division multiplexing.

In a particular aspect of the invention, the control signal
35   is generated using a phase shifting transform, such as the
Hilbert transform.

An advantage of this method and apparatus is that the optical
signal is modulated in the optical domain on the basis of a
control signal developed in the electrical domain. In other
words, the optical signal is modulated without "completely"
5 converting it into electrical form. This allows converting
optical double sideband signals to single sideband signals
without converting the original signal to the electrical
domain, which may distort the signal.

10 The filter of the present invention advantageously adapts to
the shape of the incoming optical signal. It shall be
appreciated that the exemplary filter illustrated here
applies particularly to intensity modulated signals. This is
because the chosen filter filters power signals,
15 mathematically expressed in terms of a square root
formulation in the equation. This should be no problem in
practice as generally most signals are intensity modulated.
In any event, another filter may be employed with the basic
concept of the invention thereby obtaining the previous
20 advantages for any signal shape. This means that the
suppression is verified for optical signals with any optical
bandwidth and spectrum shape. Using fixed optical filters,
the suppressed power in one of the sidebands changes
according to the used pulse shapes. However, in the case of
25 the proposed filter, a replica of the original pulse shape in
the electrical domain is obtained, and the invention
generates therefrom an electrical signal to suppress the
sideband according to the original pulse shape. In this way,
the invention is said to adapt to the optical pulse shape.
30

A further advantage is that no amplitude distortion is
introduced in the optical signals when direct detection
systems are used.

35 Another advantage of the invention is that the optical
bandwidth is reduced to half, doubling the number of channels
in WDM systems.

In addition, the OSSB signals are more tolerant to chromatic
dispersion introduced by transmission in the optical fiber
and allow electrical dispersion compensation. A full

5   appreciation of the dispersion effect can be ascertained from
the article by M. Sieben, et'al., "Optical single sideband
transmission at 10 Gb/s using only electrical dispersion
compensation", IEEE Journal of Lightwave Technology, vol. 17,
n° 10, Oct. 1999, pp. 1742-1749.

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Brief Description Of The Drawings.

The following figures illustrate at least one example of the
15 present invention.

Figures 1a and 1b illustrate SSB and DSB, respectively;

Figures 2a and 2b illustrate detuned filtering;

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Figure 3 illustrates an antiquated SSB filter;

Figures 4a-4c illustrate the effects of crosstalk;

25 Figures 5a and 5b illustrate the present invention; and

Figures 6a and 6b illustrate an example of filtering using
the present invention.

30

Detailed Description.

The proposed configuration for the adaptive optical filter
500 of the present invention to convert an input optical
35. signal 502 to obtain the OSSB signal 504 is presented in
Figure 5a. The input optical signal 502 is fed to a
splitter, such as the optical tap 506, that diverts a portion

of the power of the input optical signal. The portion not
diverted is optically phase modulated in the optical domain
by an optical phase modulator 508. An optical delay line 510
may optionally be inserted in order to take into account
5   element delays in the electrical processing.

To continue, a photodetector 512 converts the portion of the
power diverted by the optical tap 506 into an electrical
signal. The photodetector 512 may be a photo-electric diode,
10   for example. Using the photo-diode, the electrical signal
traces the carrier signal of the input optical signal,
thereby producing the envelope, or information signal of the
optical signal.

15   The converted electrical signal is then utilized to generate
a filtering control signal that tracks the shape required to
obtain the single sideband of the input optical signal. In
this case, the present invention employs a phase shifting
type transform. In one aspect of the invention, the Hilbert
20   transform was found to have advantageous characteristics that
provide excellent tracking of the shape of the optical
signal. A gain control element 516 sets the correct bias and
modulation voltages based on the input requirements of the
optical phase modulator. In a variant of the invention,
25   there is further provided an electrical processing unit 518
that serves to reshape the converted electrical signal.

The invention may be considered to have two separate
portions, or domains. The optical domain 522 processes that
30   portion of the input optical signal in the optical domain,
whereas the electrical domain 524 processes that portion of
the signal converted into an electrical signal in the
electrical domain.

35   While not the primary part of the invention, one aim of the
invention is to prepare the OSSB signal for WDM processing.

To that end, and for completeness, there is shown a WDM
component 526 that WDM multiplexes the OSSB signal 504.

Now that the physical layout of Figure 5a has been described,
5   the operation of the invention will now be set forth in
reference to the elements shown. The optical input signal
502 is split by the optical tap 506 into two components. In
one aspect a portion of the power spectrum is diverted. One
of these power components is forwarded to the optical phase
10   modulator 508. The other component is sent to the
photodetector 512.

The output electrical field of the optical phase modulator,
expressed by $E_{out}(t)$, can be represented by:
15

$$E_o(t) = E_{in}(t) \cdot \exp\left[j \cdot g(t) \right] \quad (1)$$

where t is the time and $g(t)$ is the electrical drive signal.
$E_{in}(t)$ is the electrical input signal in the optical phase
20   modulator. Optical phase modulators are currently available
in the market and the specifics of which will not be herein
described.

Using the optical delay line 510 adjusted to the particular
25   electrical components may account for possible delays in the
electrical domain 524. This optical delay takes account of
non-ideal components that are not perfect in the real world
in order to align the optical signal with the electrical
signal.
30

The photodetector 512 converts the optical signal to the
electrical domain. The electrical signal represents the
information signal of the input optical signal. This may be
accomplished using a photodiode that tracks the envelope of
35   the input optical signal.

As already mentioned, the converted electrical signal may
need to be reshaped. If the converter is non-linear, for
example, it will alter the shape of the signal. In order to
obtain the expected shape of the signal, the electrical

5 analog processor 518 is provided. Normally, the signal
expected is logarithmic and, thus, the electrical processor
518 utilizes a logarithmic function. This may be given by
the following logarithmic function f(x):

10
$$f(x) = 0.5 \cdot \log(x) \quad (2)$$

where x is the electrical signal at the output of the
photodetector. This response can be obtained by a nonlinear
electrical amplifier. Two alternative electrical analog

15 processors are shown further in this document.

After the electrical processing, the phase shifting transform
function is applied to the converted electrical signal. In
the preferred mode, the transform is an electrical Hilbert

20 filter (514). In terms of equation (2), the Hilbert filter
is used to obtain the Hilbert transform of $f(x)$. The response
of the proposed invention is adaptive, as the response of the
complete configuration presented in Fig. 5 a depends on the
optical signal pulse shape.

25
The gain control block 516 then corrects bias and modulation
voltages of the filtered electrical signal that are to be
applied to the optical phase modulator. Since these are
based on the specific physical requirements of the optical

30 phase modulator, this is left to the skilled practitioner to
determine from the product literature.

In more detail, the transform selected for the invention is
of the phase shift type. Essentially, there are three

35 methods in order to suppress power. These are the phase
shift method, detuned filtering and the known Weavers method.
The invention has determined that the phase shift method has

advantages over the others. One reason for this is that the
Hilbert transform suppresses spectrum components.

The advantages of the Hilbert transform will be better
5   understood with reference to K. Powers' article, "The
compatibility problem in single-sideband transmission", Proc.
IRE, vol. 48, pp. 1431-1435, August 1960, which describes how
the phase modulation introduced suppresses one sideband. In
distinction to the present invention, Powers does not
10   recognize the potential for using the Hilbert transform for
suppressing optical sidebands. Clearly, Powers nowhere
describes how a Hilbert transform could be applied to the
optical field.

15   In essence, Powers reveals that undistorted detection of
"standard" SSB signals is impossible using conventional
envelope detectors. While Powers discusses in detail what
causes the distortion, we will not delve into the
mathematical analysis here but defer to the cited text.
20   Consider $\alpha(t)$ the electrical field envelope modulated with
the information signal, where t is time. In order to resolve
the identified problems, Powers theorizes that sideband
suppression is achieved by introducing a phase modulation to
$\alpha(t)$. The required phase is given by a signal in quadrature
25   to the logarithm of $\alpha(t)$. Powers expresses this
mathematically according to the following expression (3):

$$\psi(t) = \alpha(t)\exp\left[\frac{i}{\pi}\int_{-\infty}^{\infty}\frac{\log\alpha(\mu)}{t-\mu}d\mu\right] \quad (3)$$

30   The above expression indicates that the envelope $\psi(t)$ may be
detected without distortion from the information that has
been transported in the signal $\alpha(t)$ as a factorial of the
modulating function performed by the exponential function.
In other words, the optical phase modulation is performed by
35   the exponential. Based on this, Powers postulates that
distortionless detection of the envelope may be obtained

using a square-law detector. The signal in quadrature to the
logarithm of α(t) is provided by the Hilbert transform of
logarithm of α(t). The Hilbert transform of logarithm of
α(t) is represented by the expression inside the brackets,
5   removing *i* (the *i* is used to obtain only a phase modulation).
The Hilbert transform of a signal x(t), HT[x(t)], is given
by:

$$HT\left[x(t)\right] = \frac{1}{\pi}\int_{-\infty}^{\infty}\frac{x(\mu)}{t-\mu}d\mu \quad (4)$$

10
In expression (4), the integrating order is μ. The use of
the integral and the term $1/\left[\pi\cdot(t-\mu)\right]$ are related with the
Hilbert transformation. $x(\mu)$ is the signal to be transformed
by the Hilbert transformer.

15
As mentioned before, two alternative electrical analog
processors can be applied in order to obtain sideband
suppression using phase modulation. Both are based on a phase
modulation proposed by Villard [see S. Hahn, "*Hilbert*
20   *transforms in signal processing*", Artech House Publisher,
Boston, 1996.]. The envelope ψ(t), obtained using such phase
modulation, is given by:

$$\psi(t) = \alpha(t)\cdot\exp\left[i\cdot HT\left(\alpha(t)\right)\right] \quad (5)$$

25
In this case, complete sideband suppression is unattained, as
expression (5) is based on mathematical approximations of
Taylor expansions. The first alternative processor makes use
of the non-linear function f(x), given by:

30                                  $$f(x) = \sqrt{\frac{x}{\bar{x}}} \quad (6)$$

where $\bar{x}$ is the mean value of x. With the proper setting of
the gain control block, the envelope described by (5) is
obtained. The second alternative processor makes use of the
assumption that the square of α(t) has a similar shape to
35   α(t). As an example, the square of a rectangular pulse with

amplitude 1 is still a rectangular pulse with amplitude 1.
Under this assumption, the third alternative processor makes
use of the function $f(x)$, given by:

5

$$f(x) = \frac{x}{\overline{x}} \quad (7)$$

The invention does not blindly follow the Powers theorem or,
for that matter, theorem's that may be alternatively used
10   with the invention such as the Villard theorem) but modifies
his theorem according to the specific arrangement of the
invention. In the case of the invention, $\alpha(t)$ is the
electrical field envelope modulated with the information,
present in the input of the proposed apparatus. Portion of
15   the power present at the input of the invention is extracted
to the electrical control circuit. At the input of the
electrical control circuit, the square-law detector squares
the electrical field, which is a portion of the total power
at the input of the proposed apparatus. In order to account
20   for this, we take the square root of the electrical signal
using the function f(x), given by (2).

An alternative configuration in the present invention is
shown in Figure 5b. In this case, Figure 5b is similar to
25   the situation in Figure 5a. Here, the phase modulation is
performed by the structure 528 with two Mach-Zehnders 528a, b
in parallel. The optical field at the output is given by:

$$E_{out}(t) = E_{in}(t) \cdot \exp\left[j \cdot g(t)\right] = E_{in}(t) \cdot \left\{\cos\left[g(t)\right] + j\sin\left[g(t)\right]\right\} \quad (8)$$

30

The term cos[g(t)] can be obtained at the output of the upper
Mach-Zehnder (MZ) and $j \cdot$sin[g(t)] can be obtained at the
output of the lower MZ. While this may be easier to
implement mathematically, the configuration presented here is
35   more complex compared with the configuration presented in
Figure 5a.

With the present invention thus far described, an OSSB signal
may be obtained without distortion. As understood from the
above, particularly with respect to Figure 5a and 5b, the
5   optical SSB signal is obtained without converting the
complete input optical signal to the electrical domain. This
allows converting optical double sideband signals to single
sideband signals without converting the original signal to
the electrical domain.
10

Further, no amplitude distortion is introduced in the optical
signals when direct detection systems are used. This can be
verified by applying the square-law detection to the output
electrical signal, given by expression (9) here:
15

$$\left|E_{out}(t)\right|^2 = \left|E_{in}(t)\cdot\exp\left[j\cdot g(t)\right]\right|^2 = \left|E_{in}(t)\right|^2 \quad (9)$$

As heretofore mentioned the optical bandwidth is reduced to
half, doubling the number of channels in WDM systems by
20   virtue that the invention employs SSB. It was also mentioned
that the OSSB signals are more tolerant to chromatic
dispersion introduced by transmission in the optical fiber
and allow electrical dispersion compensation.

25   The proposed filter adapts to the shape of the incoming
optical signal, obtaining the previous advantages
particularly to those signals belonging to intensity
modulated signals. This means that the suppression is
verified for optical signals and, particularly for intensity
30   modulated optical signals, with any optical bandwidth and
spectrum shape.

It will also be appreciated from the above that the invention
adapts to different shapes of the input optical signal.
35   Distinct pulse shapes can be used to modulate the information
into an optical carrier. The occupied bandwidth of the

modulated optical signal changes according to these pulse
shapes.

In addition, the invention solves the fore-mentioned problems
5   of crosstalk. This is shown in Figures 6a and 6b, wherein
the invention is applied to individual channels (1-n) of the
present invention as generally indicated by reference numeral
602. As can be seen using the present invention, the
multiplexed output signals (f1-f4) 604 are accurately SSB
10   filtered. The proposed invention can be applied to the
individual optical channels at the input of the dense WDM
equipment and a broadband multiplexer can be used to
aggregate the channels without distortion.

15   Although the present invention has been described with
reference to particular embodiments, it shall be appreciated
that modifications to the invention may be practiced within
the spirit and scope of the invention.